Boundary-Layer Flow Dynamics Concerning Forward Swept Wings

Arjay R. Mirchandani

Yorktown High School, 2727 Crompond Road, Yorktown Heights, NY 10598, United States

arjay.mirchandani@yorktown.org

Abstract

Air travel has two major issues; plane crashes caused by loss of control and its contribution to pollution. Aircrafts could employ a new wing orientation, forward swept wings, which would increase the effectiveness of the rear wing set, thereby increasing the control given to the pilot. Other studies suggest that forward swept wings are more efficient than the contemporary rear swept wings. If aircrafts became more efficient, then they could fly the same distance without consuming as much fuel, thereby decreasing air pollution emissions. This experiment measured the efficiency ratio (lift-to-drag ratio) as a proxy for fuel efficiency. I utilized force sensors to measure lift (upward force) and drag (frictional force) on 3D printed wing models in order to create the efficiency ratio (lift/drag). This ratio, in turn, allows for comparisons of efficiency concerning differing sweep orientations. It was found that forward swept wings were more efficient than rear swept wings at subsonic speeds. This warrants future research concerning the fuel efficiency of forward swept wings at varying speeds and angles of attack in direct comparison with rear swept wings.

Keywords

Forward Swept Wings; Swept Wings; Efficiency Ratio; Lift/Drag; Wind Tunnel

Introduction

General Problem

In 2013, over 8 million people were flying daily and while air travel is a widely utilized mode of transport, it has its fair share of problems.[1]

Two of the major issues with planes are the negative impacts on the environment as well as loss of control (usually stemming from pilot error). It has been estimated that aviation in developed countries, such as the United Kingdom, generates approximately 13%-15% of greenhouse gas emissions.[2]

Additionally, plane crashes due to loss of control is another issue and preliminary estimates suggest that private planes caused 22 deaths per two million travel hours. This fatality rate is substantially higher than the automobile fatality rate; one death per two million travel hours.[3] The loss of control that occurs in airplanes has a few technological nullifiers, such as winglets and a saw-tooth, which inhibit destabilizing airflow. (Table 1)

Fatality Rate for Differing Types of Aviation

Type of Flight	Fatalities per million flight hours
Airliner (Scheduled and nonscheduled Part 121)	4.03
Commuter Airline (Scheduled Part 135)	10.74
Commuter Plane (Nonscheduled Part 135 - Air taxi on demand)	12.24
General Aviation (Private Part 91)	22.43

Planecrashinfo.com

Table 1: Fatalities for different types of air travel. The "Part #" is the classification of different types of aircraft and thus have different flight codes and regulations.

Current Nullifiers for Loss of Control

Devices like the winglet are incorporated into aircrafts in order to counter loss of control. However, these devices have only a limited effect, and cannot completely alleviate the issue because pilot error is the biggest factor in airplane crashes.[4] A possible solution to this would be to implement forward swept wings which are a new type of wing that addresses the loss of control through a different path of airflow (Figures 1 & 2).

Winglets

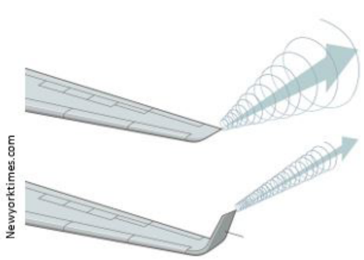


Figure 1: Diagram of winglets in action. The winglet decreases vortex generation and destabilizing airflow.

Sweep Orientations

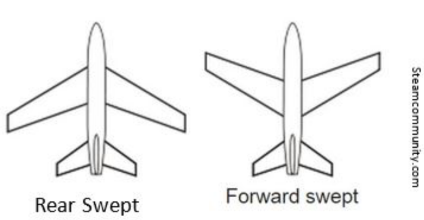


Figure 2: Comparison between rear swept and forward swept wing orientations.

The Impact on the Environment

Air travel not only emits harmful greenhouse gasses, which accelerate global warming, but the chemistry of jet emissions produces an additional warming effect. This is due to the high carbon content that is used within jet fuel, unlike many modern fuels used in other forms of travel.[5] Jet fuel, like Jet-A, has about 12 carbon atoms per molecule, while petroleum, a common base for various fuels, has about five carbon atoms per molecule.[5a, 5b] Global warming is responsible for changes in climate worldwide, leading to the need for radical changes in waste emissions[6]. The issue of carbon emissions could potentially be reduced by the implementation of forward swept wings.[15] Due to the likely improvements of efficiency, forward swept wings allow for more efficient air travel.[15, 16] This means there would be a decrease in the fuel consumption necessary for each flight, therefore reducing the amount of carbon emissions each flight produces (Figures 3 & 4). While this increase in efficiency may lead to higher demand for flights, thereby negating this improvement in efficiency (Jevons Paradox), this outcome would still result in more efficient flight from aircrafts. Furthermore, the probability of this outcome is unlikely, due to the history of similar scenarios results.[17]

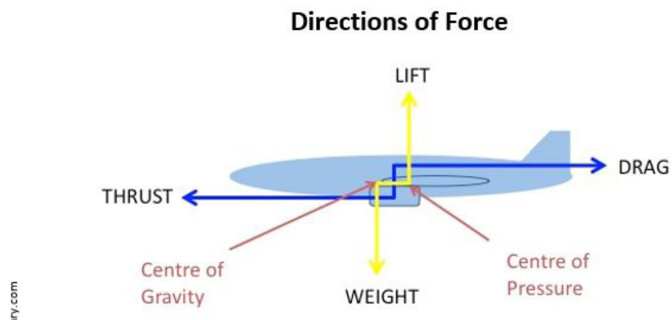


Figure 3: The direction in which a force is measured. Lift/drag defines efficiency.

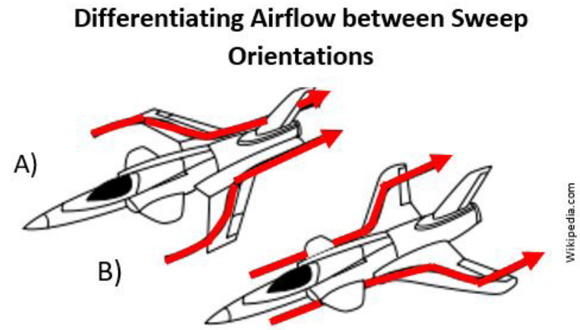


Figure 4: The airflow changes between forward swept (A) and rear swept (B) wing types.

Review of Literature

Current Aircraft Type

The most common type of airplane wing is the rear swept wing because of the high efficiency that they provide.[7] Efficiency, as defined in this experiment, is measured as the lift (upward force) divided by drag (frictional force). However, rear swept wings, while efficient, have relatively unstable airflow which makes planes much more likely to crash due to the loss of control. This instability is not fully corrected through the implementation of stabilizing components, such as winglets. The cause of the instability of rear swept wings, have been elucidated in multiple studies.[8-10]

Forward Swept Wings

The forward swept wing is a relatively unexplored option that combines high performance with reliable flight.[16] This sweep orientation was first manifested at the dawn of modern aircraft during WWII. However, this orientation was not used due to the high pressure that was put onto the wings. This pressure, after just a few flights, would critically damage the wings of the aircraft, making it unable to fly. Within the past 20 years, the prospect of using forward swept wings in contemporary aircraft design has become a viable option,[13] as the problem of high pressure was alleviated by using a modern composite material that uses fibrous layers, coupled with layered aluminum, to add to wing strength.[16] Forward swept wings lead air onto the rear wing set, causing for more stability and efficiency.[11, 12] Corrective components, such as winglets, are not required to maintain flight stability in an aircraft that uses forward swept wings due to the increased airflow displaced onto the rear wing set. Forward swept wings are predicted to be as, if not more, efficient than rear swept wings,[15, 16] which means that the forward swept orientation could generate more lift and less drag when compared to rear swept wings. With more lift and less drag being generated, the amount of fuel consumed would be lowered for flights utilizing the forward swept orientation, thereby resulting in less carbon emissions. However, even with more than ten studies focusing of the forward swept orientation, only one focused on the efficiency of the forward swept orientation due to the previously noted problem of increased pressure on the wings. No studies thus far, focused on the efficiency of forward swept wings in direct comparison to rear swept wings.

Problem

It is unknown how efficient forward swept wings are in comparison to rear swept wings. One study used a prototype of a forward swept craft, and through the process of analyzing the data from that flight, hypothesized that forward swept wings could be more efficient than rear swept wings due to the extraordinarily effective flight results gathered by the prototype's flight.[16] This study, while finding efficiency data on forward swept wings, still leaves a gap in knowledge concerning the efficiency of forward swept wings in direct comparison to rear swept wings.

Goal

The goal of this study is to test and gather preliminary efficiency values for both forward and rear swept wings, directly comparing the values. This will be done by testing and gathering data for both forward and rear swept wing types through calculating the lift and drag forces simulated via a wind tunnel in order to conclude which orientation of wing sweep is more efficient. The impact of these findings may validate the efficiency of such wings and increase its use in modern aircraft designs. This would then lead to the alleviation of loss of control during flight, as forward swept wings give more control to the pilot through increased airflow on the rear wing-set. Forward swept wings may also reduce the negative impact on the environment created by planes, as forward swept wings may be more efficient than rear swept wings.

Methods

Introduction to Methodology

In this experiment, six models of a wing were 3-D printed because 3-D printing was the most accessible way to obtain customized models. Three of the wings created model forward swept wings and three models represent rear swept wings in order to test the efficiency of both swept wing types. The splitting of model orientations allowed for direct comparison of each sweep orientation. Of the six wing models, two of each were used at differing sweep angles (one sweep angle for each sweep direction). Sweep angles are the angles between the line fuselage/wingtip and the nose of the craft (see Figure 5 – Swept Wing Comparison). The sweep angles used were 15°, 25°, and 35° in order to test the efficiency for a variety of sweep angles. Models were used in order to calculate a preliminary estimate of how efficient forward swept wings are in comparison to rear swept wings (Figures 5, 6, and 7)

Wind Tunnel Design

Figure 6: Wind tunnel design. The right-hand side is where the wind tunnel collects air and the left-hand wooden compartment houses the fan. The clear section in the middle is where the models were observed and tested.

Role of Mentor

The role of the mentor in this project was to guide the student researcher through various challenges within the study. For example, the mentor provided important advice in preliminary scaling estimates of model sizes such as the taper angle (severity of diminishing thickness) and chord length (length from wing tip to wing root).

Model Template

Taken by Student Researcher

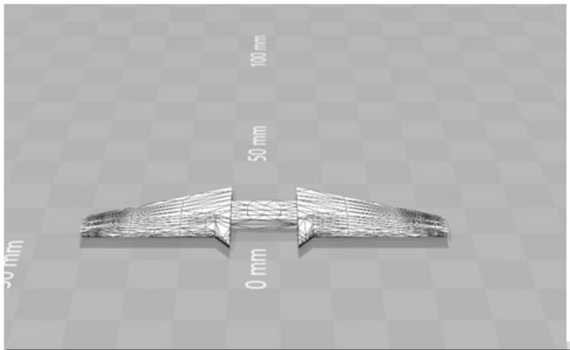


Figure 7: The original template used to create and print the models utilized in this experiment. This was later scaled to better fit the test site

Swept Wing Comparison

Taken by Student Researcher

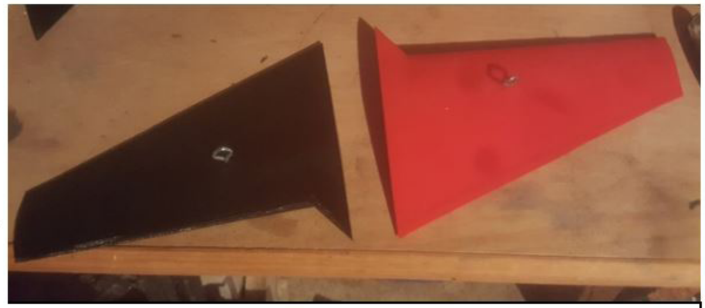


Figure 5: Depicts the comparison between rear (black) and forward (red) swept models.

Materials

This experiment utilized a wind tunnel in order to simulate air moving over a wing. The wind tunnel was borrowed from (and built by) a neighboring district. The wind tunnel was comprised of a long structure with a fan at one end to inhale air create airflow. Air moved from one open side to the other side with the fan creating the airflow at a speed of 8.5 m/s.

This experiment also utilized six different wing models that were designed to simulate swept wings. The models were created using AutoCAD 3-D modeling software. The file template was modified in order to fit the dimensions 12.93 cm x 16.68 cm x 1.61 cm as well as cropped such that there was only one wing printed per model (Fig 4).

I used force sensors to measure the magnitude of the force exerted from the wings that were attached above and in front of the leading edge of the model in order to measure lift and drag. The measurement of lift and drag enabled for calculations determining the efficiency of each model.

There was approximately 50 ft of string and six eye-hooks used in this experiment. This string was what comprised the suspension system and was what allowed the wings to be suspended in the wind tunnel. The string attached to each model on one eye-hook located at the center of balance for each model.

The suspension system's concept arose from the concept of measuring a model's lift and drag values. Contemporary systems often utilize a system that uses a clamp-like structure to hold the model in place. However, the clamp used would dampen the measurements found by the force sensors because the model would have friction on the sides. If the wings were simply floating in the wind tunnel, suspended, then the most accurate readings would be produced. Thereby, the concept of the suspension system was created; the system allows for a more accurate measurement of lift and drag forces as it does not hinder the forces exerted.

Explanation

Suspension System

The suspension system utilized a vertical string attached above the wing model in order keep to the wing model stable in the pitch axis, as well as measure the downward force on the wing. This string also kept the wing model at a constant 25^{o} angle of attack.

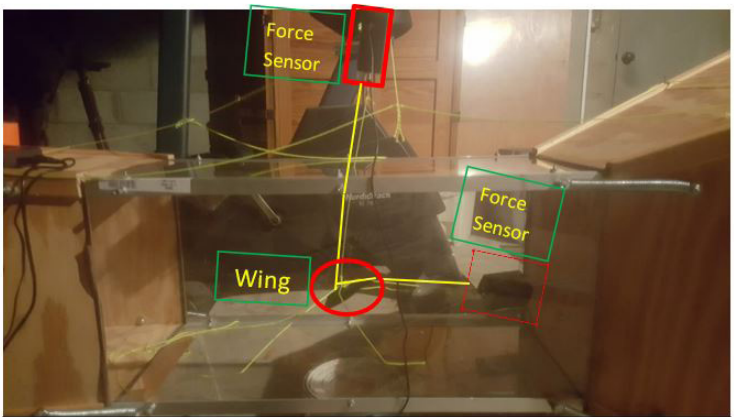
Another string was attached to the leading edge of the craft. This line limited yaw (vertical axis) instability as well as measured the frictional force exerted on the wing.

String was also attached to the "Z" axis of the craft, anchored on both sides of the craft. These lines controlled the roll direction of the craft (Figures 8 & 9)

Potential Issues

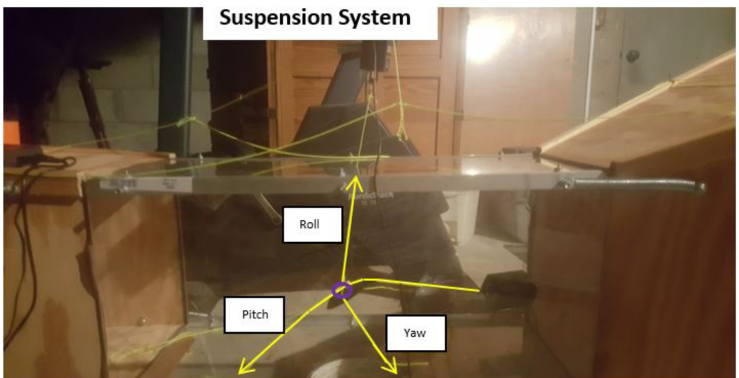
In this experiment, wing data was gathered twice in order to ensure accuracy as well as expand data points. However, there was some pitch instability in the first dataset. This was caused by the strings controlling the model because they were only anchored to one point. The second dataset addressed this problem by wrapping the roll string around the wing model. The first dataset will not be used for the calculations of results, as the slight oscillation could have mildly affected results.

Measuring Tools on the Suspension System



Taken by Student Researcher

Figure 8: Suspension system. The string has the force sensors attached which holds the wing in place. The force sensors and wing model are highlighted with red. The strings that measure lift and drag, by connecting to the force sensors, are also highlighted in bright yellow.



Taken by Student Researcher

Figure 9: Location of each pertinent string. These lines are highlighted in yellow. The strings are labeled by the direction of motion that they control. The purple circle in the middle is an eye-hook connecting the string to the wing.

Data Collection (dataset one)

Force sensors were added to the pitch line attached above the wing as well as the yaw line based from the leading edge of the wing in order to project the magnitude of the force vectors onto a display located near the wind tunnel. The magnitudes could then be recorded for data analysis. Before the wind was turned on, the magnitude for both sensors was recorded. Then, when the wind was turned on, data from each sensor was recorded every two minutes for a total of ten minutes. At the eleventh minute (one minute past when wind was turned off) another reading of force was recorded. This is a similar process to that used in many wind tunnel tests, such as Yu F. Fei and Kuo C. San.[15]

Data Collection (dataset two)

The procedure for dataset two was precisely the same of that for dataset one, except for the wind on total time and the roll string. The wind on total time was doubled to mak twenty minutes with wind. The readings still occurred every two minutes, so the data collected was double when compared to the first data set. The other change with the roll string occurred with the way it was attached. With the second data set, the roll string wrapped around the wing model to give more stability in pitch due to the fact that the string now spanned the length of the wing model, giving more points of contact to the model and as such stabilizing the movement. The added stability made the data collected more reliable, in terms of calculating efficiency, due to the increased consistency of the data (Figure 10).

Data Analysis

The first step of the analysis process starts with finding the difference in lift and was calculated by finding the average of the downward force (wind on) and subtracting it from the initial downward force (wind off). The equation modeling this calculation is $\mathbf{L = g_i - g_a}$ such that g_a is average gravity (downward force) and g_i is initial gravity. Then, the change in drag must be found by calculating the average of the frictional force (wind on) and then the initial value (wind off)

Changes in 'Roll' String

Taken by Student Researcher

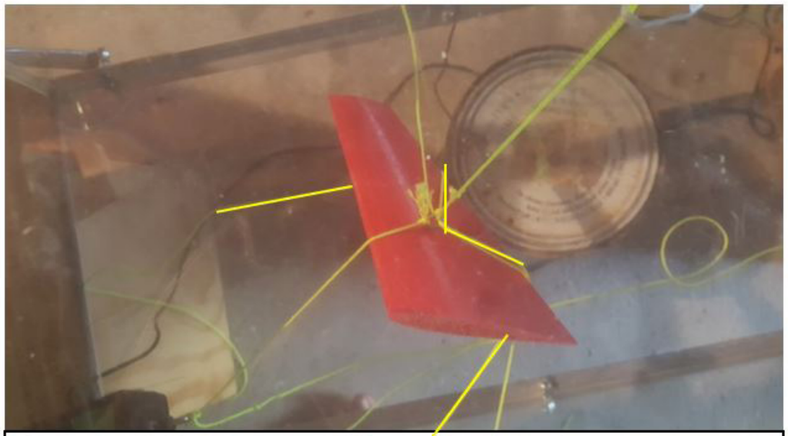


Figure 10: Bird's eye view of the suspension system in the dataset two configuration. The roll string is highlighted and wraps around the model, giving more stability and limiting the resulting oscillation

must be subtracted from this value. The equation $\mathbf{D = d_a - d_i}$ such that d_a is average lateral force and d_i is initial lateral force. Both values (change in lift and drag) should be positive in order to allow easy comparison of the two values making the resulting fraction easier to calculate. After the values of the change in lift and drag are calculated, they are put into a fraction that consists of lift/drag. The equation modeling this ratio is L/D such that L is lift and D is drag. This general efficiency coefficient allows for comparison of every wing tested in this research. A higher value in the lift over drag fraction is equivalent to a general higher efficiency at a given speed and angle of attack, both of which were kept constant in this experiment.

Results and Discussion

Overview

The goal of this research was to test and gather preliminary efficiency values for both forward and rear swept wings. Dataset 1 was not used in order to calculate the efficiency of forward swept wings due to the fact that the wing model oscillated which distorted the force sensor readings. This distortion caused the data collected to not be accurate, as it added extra force to the readings of lift and drag. Dataset 2 concluded that the forward swept wing orientation was more efficient than rear swept wings at 15^o, 25^o, 35^o. Forward swept wings were found to have a higher lift to drag (L/D) ratio at each direct angle comparison (for example: 15^o forward swept to 15^o rear swept).

Measuring lift

All tables are simplified with the word "Lift" rather than "Gravity" because the lift measurement, for both wind on and off, is actually a measurement of gravity. Lift is then calculated as the difference in gravity, which is then applied to all "lift to drag" values (Table 2).

Lift to Drag Values

The "lift to drag" (L/D) values are what define this experiment. These values are the refined data, calculated through dividing the force of lift by the force of drag, in which efficiency is measured. Each L/D value is calculated from four values: gravity (lift with wind off), lift (wind on), calibration drag (tension with wind off), and drag (wind on). Utilizing the equations $\mathbf{L = g_i - g_a}$ and $\mathbf{D = d_a - d_i}$, change in lift (Δ lift or L) and change in drag (Δ drag or **D**) were created. These values create the efficiency ratio, defined as L/D.

Lift to Drag Values of Forward and Rear Swept Wings

F-15°	R-15°	F-25°	R-25°	F-35°	R-35°
4.50	2.85	0.96	0.56	0.76	0.80
6.14	2.19	0.90	0.51	1.10	0.78
4.86	2.27	0.94	0.51	1.60	0.82
5.34	1.90	0.95	0.51	1.91	0.82
4.80	1.98	0.92	0.41	2.26	0.85
5.55	1.98	0.88	0.49	3.02	0.80
5.39	1.33	0.87	0.53	3.60	0.86
5.57	2.80	0.90	0.51	3.61	0.86
5.71	2.63	0.84	0.38	3.57	0.82
6.04	1.94	0.85	0.56	3.79	0.81

Table 2: Depicting the lift to drag (L/D) values for each experiment. The headings go by the first letter of the sweep direction followed by the sweep angle. These values were derived from the change in gravity (lift) over the change in drag (in order to compensate for tension).

Average Values

All data gathered is summarized by the average L/D value. These values represent the averaging of all gathered L/D values for each model. In short, these values represent general efficiency of each model and allow for conclusions to be made. If an average L/D value is greater than its comparison, then that model (at 8.5 m/s and angle of attack 25°) is more efficient (Table 3).

Average Lift to Drag Values

	15°	25°	35°
Forward Swept	5.39	.903	2.52
Rear Swept	2.19	.498	.822

Table 3: Each value is the basic average of each L/D value for the model.

Analysis of Data

The data collected indicates that forward swept wings are more efficient than their rear swept counterparts at every tested angle, given the constant angle of attack of 25° due to the fact that the L/D values are higher for forward swept wings. Bonferroni's Multiple Comparison Test showed that almost every comparison between efficiencies was statistically significant. Furthermore, the data shows that forward swept wings are almost twice as efficient as their rear swept counterpart at all tested sweep angles (Table 4).

P Values of Efficiency Comparison

Comparison	Significant
F-15 vs R-15	P<.001
F-15 vs F-25	P<.001
F-15 vs R-25	P<.001
F-15 vs F-35	P<.001
F-15 vs R-35	P<.001
R-15 vs F-25	P<.001
R-15 vs R-25	P<.001
R-15 vs F-35	P>.05
R-15 vs R-35	P<.001
F- 25 vs R-25	P>.05
F-25 vs F-35	P<.001
F-25 vs R-35	P>.05
R-25 vs F-35	P<.001
R-25 vs R-35	P>.05
F-35 vs R-35	P<.001

Table 4: Using Bonferroni's Multiple Comparison Test to statistically compare the average L/D values.

Comparison to Previous Research

This data differs slightly from many other previous studies in the fact that the L/D values were directly compared between forward swept wings and rear swept wings. Previous studies have looked at the efficiency (L/D values) of forward swept wings or rear swept wings, but have never made an issue of pollution by utilizing more efficient wings, the amount of fuel consumed per flight will decrease, thereby most likely leading to a decrease in carbon emissions.

Due to the increased efficiency presented by forward swept wings and due to safety issues, the widespread use of this wing should be implemented. The added control stems from the flow changes forward swept wings provide, leading more air to flow onto the rear wing-set, thereby giving more control to the craft.[16] In addition, this is one of the only studies that focused on the efficiency of forward swept wings.

Review of Goals

The goal of this study was to test efficiency values for both forward and rear swept wings through creating lift to drag ratios and comparing their values at differing angles. This was accomplished by collecting lift to drag ratios for all six models. We determined that forward swept models were more efficient.

Conclusion

This experiment was conducted in order to find the efficiency of forward swept wings and compare them to their rear swept wing counterparts. This was done through the process of suspending 3D models of wings and measuring the lift and drag forces. The readings were then converted into a lift to drag ratio that determined the general efficiency of each model. This experiment found that forward swept wings had a higher lift to drag ratio, and therefore forward swept wings were shown to be more efficient than rear swept wings. If forward swept wings were to be implemented, then aircrafts would decrease the quantity pollutants emitted as well as increase control given to pilots through flow changes. Forward swept wings have the potential to be the most efficient wing type, but they have yet to be perfected.

Acknowledgements

To my parents: Rajesh and Jann Mirchandani
To my teachers: Michael Blueglass and Rachel Koenigstien
To my mentors: Justin Czewiski and Timothy Takahashi

References

1. Iata. “Search.” IATA, 31 Dec. 2013, www.iata.org/pressroom/pr/Pages/2013-12-30-01.aspx
2. Clark, Duncan. “Aviation Q&A: the Impact of Flying on the Environment.” The Guardian, Guardian News and Media, 6 Apr. 2010, www.theguardian.com/environment/2010/apr/06/aviation-q-and-a.
3. Pappas, Stephanie. “Why Private Planes Are Nearly As Deadly As Cars.” LiveScience, Purch, 7 Nov. 2017, www.livescience.com/49701-private-planes-safety.html.
4. “STATISTICS” Accident Statistics, 2017, www.planecrashinfo.com/cause.htm.
5. Walsh, Bryan. “Does Flying Harm the Planet?” Time, Time Inc., 20 Aug. 2007, content.time.com/time/world/article/0,8599,1654488,00.html.

5a. Chris Collins (2007), “Implementing Phytoremediation of Petroleum Hydrocarbons, *Methods in Biotechnology* 23:99–108. Humana Press.

5b. *Chevron Products Corporation. “Aviation Fuels Technical Review”*

6. Essick, Photograph by Peter. “Air Pollution Causes, Effects, and Solutions.” Causes, Effects, and Solutions, 29 Sept. 2017, www.nationalgeographic.com/environment/global-warming/pollution/.
7. Bauer, Matthias, Thomas Grund, Wolfgang Nitsche, and Vlad Ciobaca. “Wing Tip Drag Reduction at Nominal Take-Off Mach Number: An Approach to Local Active Flow Control with a Highly Robust Actuator System” (2016): n. pag. Web.
8. Belyaev, I. V., M. Yu. Zaytsev, and V. F. Kopiev. “Effect of Chevrons on the Slat Noise of Straight and Swept Wings.” Acoustical Physics 61.6 (2015): 715-23. Web.
9. Thomas, Christian, Shahid M. Mughal, Matthew Gipon, Richard Ashworth, and Alejandro Martinez-Cava. “Stability of an Infinite Swept Wing Boundary Layer with Surface Waviness.” AIAA Journal 54.10 (2016): 3024-038. Web.
10. Doig, Graham, Tracie J. Barber, and Andrew J. Neely. “Aerodynamic Characteristics of a Swept Wing in Close Ground Proximity at High Subsonic Mach Numbers.” Journal of Aerospace Engineering 25.4 (2012): 600-12. Web.
11. Tang, Deman, and Earl Dowell. “Experimental Aeroelastic Models Design and Wind Tunnel Testing for Correlation with New Theory.” Aerospace 3.2 (2016): 12. Web.
12. Findanis, N., and N. A. Ahmed. “Flow Studies of a Forward Swept Wing Fitted with Active Flow Control.” (2014): n. pag. Web.
13. Shajanian, Arvin, Timothy Takahashi, Brian German, Matthew Daskilewicz, and Shane Donovan. “Wing Section Thickness and Camber Allocation for Conceptual and Preliminary Aircraft Design.” 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition (2011): n. pag. Web.
14. Kirkman, Jeffrey J., and Timothy T. Takahashi. “Critical Mach Number Prediction on Swept Wings.”55th AIAA Aerospace Sciences Meeting (2017): n. pag. Web.
15. Yu F. Fei, and Kuo C. San. “Journal of Aerospace Engineering.” Boundary-Layer Flow Effects on Aerodynamic Performance of Forward-Swept Wings | Journal of Aerospace Engineering | Vol 25, Web. 22 Mar. 2017.
16. Hicks, John W., and Edwin J. Saltzman. “In-Flight Lift-Drag Characteristics for a Forward-Swept Wing Aircraft (and Comparisons With Contemporary Aircraft).” NASA Technical Paper 3414 (1994): n. pag. Web.
17. Barrett, James. “Debunking the Jevons Paradox: Nobody Goes There Anymore, Its Too Crowded.” *ThinkProgress*, ThinkProgress, thinkprogress.org/debunking-the-jevons-paradox-nobody-goes-there-anymore-its-too-crowded-7fec531b1411/

Authors

Arjay Mirchandani – A young high school student, Arjay plans on getting a dual major in college, regarding the fields of aerospace engineering and computer programming. He has not chosen which school to attend.